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convert electric energy directly into mechanical energy and offer advantages, such as high actuating resolution, high actuating power and very short response times, while their size is small. This effect is reversible in the case of piezoelectric materials; that is, a time-variable mechanical elongation of such ceramics causes , a charge displacement between the electrodes which can, in turn, be tapped as an electric sensor signal. In combination with suitable sensors and control, actuator systems can be implemented which can automatically adapt (that is, are adaptive) to changed operating conditions.

[0004] Piezoceramic actuators and sensors are typically constructed as stack actuators, elongators or bending actuators. The former consist of stacks of thin piezoceramic disks which are elongated or shortened approximately linearly along the longitudinal stack axis under an exterior electric field. The two latter consist of thin ceramic plates which, as a rule, are flatly connected with a carrier structure and elongate the latter while an electric voltage is impressed and generate an electric signal when the structure is elongated. In an asymmetrical integration into the carrier structure, or in the controlling of a bimorph in opposite directions (bimorph = actuator or sensor consisting of at least two separately bonded and mutually insulated piezoelectric wafers which are arranged in two or more planes in a parallel and congruent manner above one another), by means of the

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actuators, bending moments can therefore also be induced. When such elongation is blocked, elongators and bending elements can be electrically controlled to transmit forces to the corresponding structure and, to a certain degree, increase its stiffness.

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[0011] This actuator type is permissible only for temperatures of up to maximally 100°C; at higher temperatures, parts of the plastic materials used for the encapsulating and gluing-together of the individual layers start to decompose; this generally leads to a massive delamination of the actuator, and to catastrophic destruction. However, modern high-performance composite materials are generally manufactured at temperatures of up to 180°; sometimes, an additional cure cycle (post-cure) of the components at still higher temperatures will be required.

[0012] The described tails of the QuickPack® actuators are incompatible with a structurally conformal integration in fiber composites, because guiding of the electric feed line out of a fiber composite component requires severing the cover layers on the actuator. The latter is necessarily accompanied by an intolerable reduction of strength, destroying the advantage of a structural integration.

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[0016] These and other objects and advantages are achieved by the fiber composite according to the invention, in which

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the piezoceramic sensor or actuator integrated therein has feed lines for the sensor or actuator in the form of electrically insulated thin wires which extend out of the fiber composite perpendicular to the laminate layers, so that the fibers are not severed by the leading-out of the feed lines, but are only slightly pushed apart. This arrangement achieves the integration of the actuator or sensor into the fiber composite structure without a significant reduction of the strength characteristics of the component.

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[0025] As mentioned above, the tails of encapsulated piezoceramic actuators (such as QuickPack® actuators) are not compatible with a structurally conformal integration in fiber composites because the leading of such an electric feed line out of a fiber composite component requires severing the cover layers, necessarily resulting in an intolerable reduction of strength. The tail is therefore cut off close to the actuator and the copper strip conductors applied to the polyimide foils are partially ground, for example, by means of a fine diamond milling cutter. Electric connection can then be made via thin cables which are soldered onto the copper strip conductors by means of a suitable solder which must not liquefy in the environmental conditions existing during the production. Care should be taken in this case that the soldering point does not thicken and that the entire connection area does not exceed the thickness of the actuator. When the cables (such as a copper . 0.2 mm or . 0.5 mm insulated wire) are selected, care

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cont'd.* should be taken, on the one hand, that they are sufficiently electrically insulated and, on the other hand, will withstand the environmental conditions during the production without damage and in a fully operable manner. Likewise, the line cross-section, corresponding to the later operating range of the actuator, must be selected such that no heating of the electric feed line, and thus no fault or even damage to the structure, can occur. Another advantage of the modification of the electric feed line, as described, is a significant simplification of the handling of the feed lines in further production processes, because, for example, their length, can be adjusted arbitrarily.

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cont.* [0027] In the structural integration of the actuators into the fiber composite, generally a large number of different configurations are possible. Three specific configurations are illustrated as examples in Figure 2. In all three, the actuator A is integrated in the fiber composite component; that is, the actuator is covered on both sides by at least one layer of the laminate L. In the construction according to Figure 2.a, no laminate layers are severed for the integration of the actuator, which is placed between two adjoining layers of the laminate L. In the embodiment according to Figure 2.b, recesses for the actuator A are provided in several laminate layers, while Figure 2.c is a mixed form of the two previously described embodiments according to Figures 2.a and 2.b. In Figure 2.c, individual layers are provided with recesses,

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cancel . whose entire thickness is, however, less than the height of the actuator A. The layers provided with the recesses are adjoined by layers without recesses. During the curing of the component, the resulting pockets H will be filled with resin.

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a6 [0029] By means of a template and a fine needle, penetration points for the electric feed lines are marked in the cover layers (layers above the actuator), to which the peel-ply has been applied on one side. This technique ensures that the reinforcing fibers of the structures are only pushed apart, and not severed, which finally has a considerable effect on the strength of the component. Subsequently, the electric feed lines are guided through the cover laminate and tightened, and the laminate is pressed together with the remaining component. In principle, several wires can also be led through a common opening. In all operating steps, particularly consolidation in a vacuum, a buckling of the cables is to be avoided.

[0030] A standard construction according to Figure 3 is used for the baking of the fiber composite component in the autoclave. The reference numbers indicate the following:

- 1 base plate
- 2 edge strip
- 3 Teflon peel-ply
- 4 metal pressure plate
- 5 release film

- 6 sealing tape (mastic)  
7 vacuum bag  
8 breather cloth  
9 vacuum breach unit  
10 fiber composite

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[0031] Instead of a massive pressure plate (normally, polished aluminum plate with  $t \geq 12$  mm), a thin metal pressure plate 4 is used, as separately illustrated in Figure 4. As a result of the correspondingly reduced stiffness, the slight thickening in this area, which is generally caused by the integration or application of the actuator, is taken into account; that is, pressing-out of the matrix in the corresponding section, when pressure is applied in the autoclave, will be reduced, and the mechanical characteristics of the fiber composite are therefore only slightly influenced.

[0032] Aluminum sheets of a thickness of 2 mm were found to be suitable for use as metal pressure sheets. At the points at which the electric feed lines emerge from the component (in the described process, any site on the surface of the fiber composite component), bores are made in the metal sheets. The latter have a diameter  $d$  which, in the case of the utilized thickness of the metal pressure sheet, should be approximately 1 mm above the diameter of the used electric conductor. From the laminate side, these bores are counterbored a good 1 mm deep and are deburred. Finally, the metal pressure sheet is

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*a<sup>7</sup> cont.* [0034] When preparing the autoclave setup, care should be taken that the wires are tightly guided through the metal pressure sheets and, during the cure process, are not damaged or sheared off by the metal pressure sheet. As soon as the metal pressure sheet and the edge strips 2 are fixed, the bores, from which the wires are guided through the metal pressure sheet, are sealed off on both sides by means of several strips of sealing tape 6 and the wires are then loosely fixed on the metal sheet.

[0035] During the curing of the component, the pressure values and temperature values are particularly within the following ranges:

Pressure: 3 - 10 bar,

temperature: 120 - 220°C.

[0036] The described process and resulting structure have the following advantages:

- Because the wires are guided out of the laminate perpendicularly to the surface, which can occur at any location because the wires can be continued

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without any significant disturbance of the laminate characteristics in the plane, the usually required edge trimming of the components is permitted. This was not possible in such a simple manner in the prior art solutions disclosed in the literature.

- The use of metal pressure sheets instead of massive pressure pieces largely maintains the characteristics of the fiber composite structure, so smoother geometrical transitions can be created in the component in the areas of the integrated actuators, while mechanical stress concentrations are significantly reduced.
- By guiding the electrical feed lines through the metal pressure sheet precisely at the points at which they emerge from the laminate, the perfect surface quality of the component is completely maintained.
- Countersinking of the bores in the metal pressure sheet significantly reduces the danger of damage to or of shearing off the electric feed lines, and leads to higher permissible tolerances during the manufacturing.

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- The use of sealing tape at the outlet points protects the electric feed lines on the metal sheet against (breaking-off) buckling.
  - Since pressure is applied in the autoclave (generally 7 bar outside the autoclave construction) before the rise in temperature (generally 180°C) liquefies the matrix, a portion of the sealing tape applied around the bores is pressed through the gaps between the wire and the metal pressure sheet and completely fills the truncated cone formed by the countersinking of the metal sheet. (No air pockets are created in this case, because of the fact that the component inside the autoclave construction is simultaneously acted upon by the vacuum.)

[0037] This results in the following advantages:

- Excellent sealing-off of the bores; no resin outflow with the corresponding negative consequences on the mechanical characteristics of the component.
- Absolutely planar surface at the points of the exiting of the wire from the laminate by the isostatic pressure distribution already before the liquefaction of the matrix.

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- Because the sealing tape is pressed in the gap between the metal pressure sheet and the wire, no gluing-together of the metal pressure sheet and the wire can occur by the emerged matrix.
  - The small gap between the metal pressure sheet and the wire minimizes the tensile or pushing force to be overcome for lifting-off the metal pressure sheets after the curing of the component, minimizing the danger that the wires are torn off. The metal pressure sheets can easily be detached from the component.
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[0039] Detailed studies have demonstrated that the catastrophic destruction of the QuickPack® actuators in the case of the above-described processing according to the prior art is most probably caused by sublimation of the internal adhesive layers and partially sublimation of the thermoplastic spacers at temperatures above approximately 100°C., which cause large-surface delaminations in the actuator. Such destruction of encapsulated piezoceramic actuators can be prevented by an application of pressure applied simultaneously with the temperature load.

[0040] The cure cycle of some matrix systems includes a tempering process (post-cure for the complete cross-linking of the matrix) which, primarily for reasons of cost, is not

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Cmce. necessarily carried out in the autoclave, in the case of fiber composite structures with QuickPacks® embedded according to the above-described process. Accordingly, this tempering process can be carried out only by the application of unidirectional pressure and heat. For the carbon-fiber-reinforced plastic system (T800/5245C) used here, a tempering process of 4 h @ 210°C is provided. However, in order to avoid stressing the actuators above the temperature level existing in the autoclave, the temperature of the tempering process was lowered to this temperature (180°C), so that the duration for complete post-cure-cross-linking simultaneously had to be significantly increased. By means of the ILS -values (interlaminar shear strength, compare EN 2563) of a number of samples, the modified post-cure cycle for the carbon-fiber-reinforced plastic system used here was determined to be 16h @ 180°C, a pressure of 7 - 10 bar being applied in a hot press. Here, different forms of the (mechanical) application of pressure are definitely also conceivable, which do not require high mechanical expenditures. In order to ensure a uniform application of pressure to the actuators, a rubber layer of a thickness of between 15 to 20 mm was found to be suitable which is kept away from a direct contact with the component by several layers of a dense Teflon film. The danger of mechanical depolarization of the actuators or of transverse pressure failure of the fiber composite does not exist at these pressures.

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